Interstellar Media in the Magellanic Clouds and other Local Group Dwarf Galaxies

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Abstract. I review the properties of the interstellar medium in the Magellanic Clouds and Local Group dwarf galaxies. The more massive, star-forming galaxies show a complex, multi-phase ISM full of shells and holes ranging from very cold phases (a few 10 K) to extremely hot gas ($> 10^6$ K). In environments with high UV radiation fields the formation of molecular gas is suppressed, while in dwarfs with low UV fields molecular gas can form at lower than typical Galactic column densities. There is evidence of ongoing interactions, gas accretion, and stripping of gas in the Local Group dwarfs. Some dwarf galaxies appear to be in various stages of transition from gas-rich to gas-poor systems. No ISM was found in the least massive dwarfs.

1 Introduction

There are currently 36 known and probable galaxy members of the Local Group within a zero-velocity surface of 1.2 Mpc. Except for the three spiral galaxies M31, Milky Way, and M33, the irregular Large Magellanic Cloud, and the small elliptical galaxy M32 all other galaxies in the Local Group are dwarf galaxies with $M_V > -18$ mag. In this review I will concentrate on the properties of the interstellar medium (ISM) of the Magellanic Clouds and the Local Group dwarf galaxies, moving from gas-rich to gas-poor objects. Recent results from telescopes, instruments, and surveys such as *NANTEN*, *ATCA*, *HIPASS*, *JCMT*, *ISO*, *ROSAT*, *FUSE*, *ORFEUS*, *STIS*, Keck, and the *VLT* are significantly advancing our knowledge of the ISM in nearby dwarfs and provide an unprecedented, multi-wavelength view of its different phases. For a detailed review of the properties of all Local Group galaxies see [73].

2 The Magellanic Clouds

2.1 The Large Magellanic Cloud

At high Galactic latitude and a distance of only ∼50 kpc, the Large Magellanic Cloud (LMC) is one of the best-studied galaxies in the Local Group. With $0.5 \cdot 10^9$ $M_\odot$ [36], the gaseous component (neglecting He) contributes ~ 9 % to the total mass of the LMC ($5.3 \pm 1.0 \cdot 10^9$ $M_\odot$; [1]). The gas to dust ratio is four times lower in the LMC than in the Milky Way [39]. The total diffuse H_2 mass is $8 \cdot 10^6$ $M_\odot$, $< 2\%$ of the LMC's H I mass and ∼1/9th of the Milky Way's fraction [72]. The reduced H_2 fraction may imply enhanced destruction through UV photodissociation in low-metallicity environments or suppressed

H_2 on dust grains that H_2 [72]. While high dust content is correlated with high H_2 abundances, H_2 does not trace CO or dust *per se* [72].

CO shows a strong correlation with H II regions and young (< 10 Myr) clusters, but only little with older clusters and supernova remnants (SNRs) ([19], cf. [2]). Massive CO clouds have typical lifetimes of ~ 6 Myr and are dissipated within $\sim$3 Myr after the formation of young clusters. CO clouds exist also in quiescent areas without ongoing star formation; potential sites of future activity. Overall, the LMC clouds haver lower CO luminosities than in the Milky Way and higher gas to dust ratios [19]. Individual cloud masses range from a few 10^4 $M_\odot$ to $2 \cdot 10^6$ $M_\odot$. With 4 to $7 \cdot 10^7$ $M_\odot$ the estimated molecular gas mass of the LMC amounts to 8 to 14% of its total gas mass [19].

H I aperture synthesis maps of the LMC have revealed an ISM with a turbulent, fractal structure that is self-similar on scales from tens to hundreds of pc [18], likely due to the energy input of OB stars and supernova explosions. The flocculent ISM consists of numerous shells and holes surrounded by broken H I filaments [36]. At very large scales supershells dominate. 23 H I supershells (i.e., holes with sizes that exceed the H I scale height) and 103 giant shells (sizes below the H I scale height) were identified [37]. Many of the giant shells interlock or collide with one another, or occur at the rims of supershells. They probably result from winds of recently formed massive stars in a propagating-star-formation scenario. Generally, the H I shells show little correlation with the optically dominant H II shells, which suggests that H I shells live longer than the OB stars that caused them initially [37]. H I associated with H II typically exceeds the size of the ionized regions.

The overall appearance of the H I disk of the LMC is symmetric, does not show obvious correlations with the optical bar, and reveals spiral features [36]. Its southernmost "spiral arm" connects to the Magellanic Bridge, the tidal H I overdensity between the LMC and the Small Magellanic Cloud (SMC).

Photoionization is the main contributor to the optical appearance of the ISM at $\sim 10^4$ K in the LMC and other gas-rich, star-forming galaxies. The LMC has a total Hα luminosity of $2.7 \cdot 10^{40}$ erg s^{-1}. 30 to 40% are contributed by diffuse, extended gas [35]. Nine H II supershells with diameters > 600 pc are known in the LMC [48]. Their rims are marked by strings of H II regions and young clusters/OB associations. The standard picture for supershells suggests that these are expanding shells driven by propagating star formation (e.g., [47]). However, an age *gradient* consistent with this scenario was not detected in the largest of these supershells, LMC4 [15]. Nor are the supershells LMC1 [53], LMC2 [52], and LMC4 [16] expanding as a whole, but instead appear to consist of hot gas confined between H I sheets and show localized expansion. Supershells in several other galaxies do not show evidence for expansion either [52], nor for the expected young massive stellar populations [57].

More highly ionized gas can be effectively traced through ultraviolet absorption lines from species such as such as C IV (10^5 K), N V ($2 \cdot 10^5$ K), and O VI ($3 \cdot 10^5$ K; these temperatures are valid in the likely case of collisionally ionized gas). C IV and O VI are detected along sight lines across the entire

LMC, spatially uncorrelated with star-forming regions. Its velocities indicate that it is likely part of a hot, highly ionized corona of the LMC ([75], [31]).

Shock heating through fast stellar winds and, more importantly, supernova explosions are the primary creation mechanisms for hot gas with $\geq 10^6$ K [11]. Diffuse hot gas in supershells, however, contributes only 6% to the total X-ray emission from the LMC [54]. LMC2, the supershell east of 30 Doradus, has the highest X-ray surface brightness of all the supergiant shells in the LMC. The second highest X-ray surface brightness comes from the yet unexplained extended "spur" south of LMC2. The largest contribution to the LMC X-ray budget comes from discrete X-ray binaries ($\sim 41\%$), followed by diffuse field emission ($\sim 30\%$), and discrete SNRs ($\sim 21\%$) [54].

Finally, the LMC is the only external galaxy detected thus far in diffuse γ-rays, which are produced by (and directly proportional to) the interaction of cosmic rays (e.g., from supernovae) with the interstellar medium [50]. The integrated flux above 100 MeV is $1.9 \cdot 10^{-7}$ photons cm^{-2} s^{-1} [65].

2.2 The Small Magellanic Cloud

The SMC is the second most massive Milky Way companion ($2 \cdot 10^9$ M$_\odot$; [79]). With a total H I mass of $4.2 \cdot 10^8$ M$_\odot$ [66], 21% of its mass are in the ISM. The SMC's dust mass, on the other hand, is only $1.8 \cdot 10^4$ M$_\odot$ [67], and its average dust to gas mass ratio is $8.2 \cdot 10^{-5}$, a factor 30 below the Galactic value. The highest concentrations of dust are found in luminous H II regions. Cold gas appears to be mostly atomic rather than molecular due to the reduced dust abundance, fewer coolants, and a higher UV radiation field ([67], [14]), which help to photodissociate H_2. Less than 15% of the H I is in cold gas, which tends to be colder than in the Milky Way (≤ 40 K vs. 50 to 100 K [14]). The diffuse H_2 mass is $2 \cdot 10^6$ M$_\odot$, $\sim$0.5% of its H I mass and 1/9th of the Galactic value, similar to the reduced H_2 fraction in the LMC [72].

Three H I supershells (> 600 pc) and 495 giant shells were detected in the SMC ([68]; [66]). These shells appear to be expanding. Their rims coincide with a number of H II regions. Their centers lack pronounced Hα emission in good agreement with their dynamical ages of $> 10^7$ years and the propagating star formation scenario proposed by [47], though detailed studies of the stellar age structure are lacking so far. As in the LMC, the ISM of the SMC is fractal [66], likely due to turbulent energy input. The idea that the SMC consists of multiple components that are distinct in location and velocity is not supported by the recent large-scale H I data and was probably an artifact of the complex shell structure of the SMC [68]. On large scales, areas of high H I column densities coincide with the luminous H II regions that form the bar and the wing of the SMC [66]. The distribution of stars younger than 200 Myr also traces these areas of recent massive star formation well [88]. Collisionally ionized gas with a few 10^5 K forms a hot halo around the SMC and shows enhanced column densities toward star-forming regions [30]. Slightly enhanced diffuse X-ray emission has been detected along the SMC bar [64].

2.3 The Magellanic Bridge and Stream

The SMC has a distance of ~ 60 kpc from the Milky Way and ~ 20 kpc from the LMC. SMC, LMC, and Milky Way interact tidally with each other, which is reflected in, e.g., the H I warp of the Milky Way disk [76], in the thickening of the LMC's stellar disk [77], its elliptical extension toward the Milky Way [74], in the star formation histories of the three galaxies ([22]; [24]; [60]), and most notably in the gaseous tidal features surrounding the Magellanic Clouds.

The LMC and SMC are connected by the "Magellanic Bridge", an irregular, clumpy H I feature with a mass of 10^8 $M_\odot$ that emanates from both Clouds [55]. Cold (20 to 40 K) H I gas has been detected in the Bridge [38], and recent star formation occurred there over the past 10 to 25 Myr [13]. Higher ionized species with temperatures up to $\sim 10^5$ K show an abundance pattern suggesting depletion into dust [40]. Interestingly, stellar abundances in the Bridge were found to be ~ -1.1 dex [61], 0.4 dex below the mean abundance of the young SMC population, which is inconsistent with the proposed tidal origin 200 Myr ago [21]. However, it is conceivable that the Bridge formed from Magellanic Clouds material that mixed with an unenriched component [61], making cloud-cloud collisions a possible star formation trigger [40].

Additional tidal H I features include the leading arm (10^7 $M_\odot$, 25° length, [55]) and the patchy, clumpy trailing arm ($10^\circ \times 100^\circ$) of the Magellanic Stream, in which no stars have been detected so far [56]. The Magellanic Stream is detected in Hα due to photoionization by the Galaxy [4]. The abundance patterns of interstellar absorption lines are consistent with those in the SMC, and the H_2 detected in the leading arm may originally have formed in the SMC [63]. Based on their abundances, additional high-velocity clouds in the vicinity may have been torn out of the SMC [42].

3 Other Local Group Irregulars

The remaining Local Group dwarf irregulars (dIrrs) are more distant from the dominant spirals, and fairly isolated. While their star formation activity and gas content generally decrease with decreasing galaxy mass, their star formation histories and ISM properties present a less homogeneous picture when considered in detail. We first present the contrasting examples of two comparatively high-mass dIrrs and then move on to the low mass end.

The H I of IC 10 (distance 660 kpc) is 7.2 times more extended than its Holmberg radius [70]. While the inner part is a regularly rotating disk full of shells and holes, the outer H I gas is counterrotating [80]. IC 10 is currently undergoing a massive starburst, which may be triggered and fueled by an infalling H I cloud ([62], [80]). Only upper limits have been established for the diffuse X-ray emission [59], which may be due to the high foreground absorption toward IC 10. A non-thermal superbubble was detected that may be the result of several supernova explosions [81]. The masses of the molecular clouds in IC 10 are as high as 0.3 to $5 \cdot 10^6$ $M_\odot$ [51]. Owing to the high radiation field and the destruction of small dust grains, the ratio of far-infrared [C II] to CO 1–0 emission is a factor 4 larger than in the Milky Way [6], resulting in small CO cores are surrounded by large [C II]-emitting envelopes [44]. Two H_2O masers were detected in dense clouds in IC 10, marking sites of massive star formation [3]. The internal dust content of IC 10 is high [58].

NGC 6822, a dIrr at a distance of $\sim$ 500 kpc, is also embedded in an elongated H I cloud with numerous shells and holes that is much more extended than its stellar body [12]. Its total H I mass is $1.1 \cdot 10^8$ $M_\odot$, $\sim$ 7% of its total mass. The masses of individual CO clouds reach up to 1 to $2 \cdot 10^5$ $M_\odot$ [51], while the estimated H_2 content is 15% of the H I mass [33], and the dust to gas mass ratio is $\sim 1.4 \cdot 10^{-4}$ [34]. In comparison to IC 10, NGC 6822 is fairly quiescent, although it contains many H II regions. Its huge supershell (2.0×1.4 kpc) was likely caused by the passage of and interaction with a nearby 10^7 $M_\odot$ H I cloud and does not show signs of expansion [12].

The H I in low-mass dIrrs may be up to three times more extended than the optical galaxy and is clumpy on scales of 100 to 300 pc. The most massive clumps reach $\sim 10^6$ $M_\odot$. H I concentrations tend to be close to H II regions. Some dIrrs contain cold H I clouds associated with molecular gas, while dIrrs without cold H I also do not show ongoing star formation. The total H I masses are usually $< 10^8$ $M_\odot$. The center of the H I distribution coincides roughly with the optical center of the dIrrs, although the H I may show a central depression surrounded by an H I ring or arc (e.g., SagDIG, Leo A). In contrast to the more massive dIrrs, the low-mass dIrrs show little to no rotation and appear to be dominated by chaotic motions. Details are given in [41], [85], [86], [17].

4 Elliptical, Spheroidal, and Transition-Type Dwarfs

The ISM of the dwarf elliptical (dE) companions of M31 exhibits puzzling properties that are not yet understood. In NGC 205, the stellar component does not show rotation, while the H I does [87]. In NGC 185, stars and gas belong to the same kinematic system, while in NGC 147 neither H I nor molecular gas were detected [87]. In these three galaxies, the most recent measured star formation event took place 50 Myr, 100 Myr, and >1 Gyr ago, respectively ([8], [45], [28]), but these recent episodes cannot explain the differences in the ISM content. With 10^6 $M_\odot$, the amount of gas in NGC 205 is a factor of 10 below what one would expect from normal mass loss through stellar evolution, and the kinematic differences between gas and stars make this an unlikely origin [78]. In NGC 185 stellar mass loss may provide an explanation for the H I. In both galaxies, the gas is less extended than the optical body, asymmetrically distributed, and clumpy on scales of less than 200 pc. NGC 205 contains CO and dust, which are closely associated with H I concentrations on scales of 100 pc [83]. While the molecular clouds in NGC 205 closely resemble Galactic clouds, the H I envelopes of the CO clouds have much lower column densities of only $\sim 10^{20}$ cm^{-2} due to the lower interstellar UV radiation field. This implies that in dwarf galaxies with low UV radiation molecular gas may form and survive even at column densities below 10^{21} cm^{-2} as less shielding is required ([83]; see also [17]). The gas to dust ratio, which is similar to the one in the Milky Way, indicates that little dust gets destroyed in this environment. Even extremely cold dust with < 10 K was detected in NGC 205 [27].

Owing to their prominent old stellar populations, some dIrrs resemble dwarf spheroidal (dSph) galaxies. But while dSph galaxies appear to be devoid of gas, these galaxies have been detected in H I. Thus they are classified as dIrr/dSph systems, galaxies that may be in transition from low-mass dIrrs to gas-less dSphs. LGS 3, one of these transition types, is at a distance of 280 kpc from M31 and experienced low-rate star formation until 500 Myr ago [49]. Its star formation rate was not significant enough to expel its gas, and the H I distribution is nicely centered on the optical galaxy. In contrast, the dIrr/dSph galaxy Phoenix (distance ~ 400 kpc from the Milky Way), which formed stars continuously until 100 Myr ago [29], does not contain H I within the main body of the optical galaxy. However, a nearby H I cloud with $\sim 5 \cdot 10^6$ M$_\odot$ has a velocity consistent with its having originated from Phe ([69], [20]). It may have been expelled through supernova explosions (though its regular shape seems to argue against this), or ram pressure stripping [20]. Gas in two extended H I lobes appears to be within the tidal radius of Sculptor, a dSph without a young or significant intermediate-age population [32], matching its velocity [9]. The amount of gas detected is consistent with expectations from stellar mass loss through normal stellar evolution. On the other hand, the surrounding field is filled with similar clouds, suggesting the possibility of mere coincidence [10].

The upper limits for H I in the other Local Group dSphs are at column densities of a few 10^{17} cm^{-2}, well below even of expectations from mass loss through normal stellar evolution. At earlier stages in their evolution, these dSphs were evidently capable of forming stars and retaining gas over extended periods of time. Even those that are predominantly old show evidence for metallicity spreads [23]. The Fornax dSph still formed stars < 200 Myr ago [25], while sensitive H I searches did not detect any gas [82] – perhaps a galaxy one step beyond Phe, just having completed its transformation into a dSph? Claims that gas exists at larger distances from dSphs [5] were not confirmed for several of them (e.g., Leo I [84]; And V [26]). Searches for diffuse highly ionized gas only yielded upper limits (Leo I: [7]). Internal effects such as supernova explosions appear to be insufficient for removing the gas [43]. Gas loss through tidal shocks during perigalactic passages close to a massive galaxy may rid dSphs of their gas [46] and provide an explanation for transition-type galaxies and the morphology-density relation, but environmental effects cannot explain isolated, gas-less dSphs like Tucana. Hence many interesting questions concerning the ISM in dwarf galaxies remain open.

Acknowledgements. It is a pleasure to thank the organizers for their kind invitation, Y.-H. Chu and J.S. Gallagher for a critical reading of the text, and Landessternwarte Heidelberg for a quiet office where this review was completed.

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